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Autonomous Wind-Generated Electricity for Induction Motors[1]

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A wind turbine with variable-voltage, variable-frequency electrical output was used to power resistive loads and induction motors in an autonomous system. The AC system was selected because AC motors, in multiple kilowatt sizes, can be more practical than DC motors. A wind turbine which produces electricity has a lower overall efficiency than a system producing mechanical power but offers more flexibility in adapting to varying loads and in locating the wind turbine near the load. A permanent magnet alternator designed to operate with a rotor speed from 70 to 150 r/min was first operated in the laboratory. The frequency of the output varied from 30 to 65 Hz, while the voltage changed from 85 to 218 V, resulting in voltage to frequency ratios (V/f) from 2.6 to 3.3 with various loads. The alternator, with a maximum rated output of 9 kW, provided power to resistive load or induction motor loads. The tests revealed that standard three-phase, 240 V, 60 Hz, AC induction motors will operate with an input of 85 V and 30 Hz. A motor temperature rise of 40° C above ambient was not exceeded when power was supplied by the alternator to a 7.6 kW motor. System efficiencies were nearly equivalent to those obtained with utility power, even though the V/f was below that calculated from the motor's nameplate. The wind energy conversion system (WECS) was then operated in windspeeds of 3.5 m/s or greater. This WECS was capable of providing power to satisfactorily operate induction motors in an autonomous system.

Introduction

The operation of a wind turbine without interconnection to the electric utility has numerous applications. The load may be located where power distribution from a utility may not be practical or economical. A wind energy conversion system (WECS) producing mechanical power can be more efficient, but the load matching capabilities and flexibility of an electrical system can be more practical.

The United States Department of Agriculture-Agricultural Research Service (USDA-ARS) has been studying the use of wind energy to generate power for farms and rural applications. An objective of the program is to develop a system that is independent of the electric utility. It is necessary that the WECS have the capability of powering different loads so that wind power is utilized throughout the year. For this project, the less costly induction motor was used with a permanent magnet alternator-equipped WECS. All components used were commercially available.

Two prevalent methods for producing utility compatible electricity using a wind turbine are with an induction generator or an alternator connected to a line-commutated inverter [1], [2]. The induction generator with a speed increaser has a small amount of slip but operates essentially at a fixed rotor speed with a variable tip-speed ratio (blade tip-speed/windspeed). The coefficient of performance (C_p) of a rotor is a function of tip-speed ratio; therefore, the rotor with an induction generator will have a variable C_p as the windspeed fluctuates. The line-commutated inverter, which converts the alternator output to utility compatible power, is a substantial addition to the cost of a WECS. Both methods normally require excitation from the utility.

Satisfactory performance from an induction motor is generally obtained over a range of plus or minus 10 percent from rated voltage and plus or minus 5 percent from rated frequency [3]. The torque developed by the motor is approximately proportional to the square of the voltage and inversely proportional to the square of the frequency. Less than rated voltage with constant frequency will affect the power factor, efficiency, and operating temperature of the induction motor. A motor with a National Electrical Manufacturer's Association (NEMA) Class B insulation has a design life of 10,000 hours and is designed to have its insulation at a temperature no greater than 130°C at full load [4]. Higher motor temperatures than 130°C can degrade insulation and reduce motor life. The selection of motor size is a compromise between motor life, efficiency, and cost.

The variation of voltage and frequency to a polyphase stator has been a method of speed control for motors [5]. When changing frequency, it is necessary to change the applied voltage in the same proportion in order to maintain the same degree of saturation and mutual air-gap flux density. If the voltage to frequency ratio (V/f) is not maintained con-

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stant, the motor will operate at a lower efficiency and may be subjected to overloads. The constant V/f assures an almost constant-current operation for the motor and prevents thermal overload [6]. A reduction in frequency will lower the synchronous speed and result in a decrease in motor speed which may not be acceptable for some applications.

The rotational speed, voltage, and frequency of the output of a wind driven asynchronous alternator is proportional to the windspeed. The power available from the wind varies as the cube of the windspeed. The power required by a pump is proportional to the cube of the rotational speed for the pump. The variable frequency output of the alternator will vary the speed of the pump, thus providing a good match between power required and power available.

Description of Equipment

The commercially available WECS used for the project was a Windworker 10, manufactured by Windworks, Inc.[3] The variable-speed alternator produced a variable frequency, variable voltage, three-phase AC output. The three-bladed, horizontal-axis machine with a swept area of 78.5 m^2 was rated at 9 kW in a 9 m/s wind.

The speed of the alternator's rotor was regulated by varying the pitch of the blades. The blades were held in a feathered position at windspeeds below 3.5 m/s. In windspeeds greater than 3.5 m/s, a change in the blade pitch resulted in a minimum rotor speed of 70 r/min. The blades remained fixed in pitch as the windpseed increased until the rotor speed reached 150 r/min. As the alternator speed increased above 150 r/min, the blades adjusted to a lower attack angle to maintain a constant speed of 150 r/min and power output of 9 kW.

Description of Tests

The wind turbine, with a direct-drive permanent magnet alternator, was tested in the laboratory by powering the alternator with a variable-speed drive. Resistive loads and induction motor loads were used to initially assess the potential applications [7]. Several combinations of resistive loads were tested with the voltage and frequency of a representative load shown in Fig. 1. A linear output of frequency between 30 to 65 Hz was observed as alternator speeds increased 70 to 150 r/min. The voltage varied from 210 V at 150 r/min to 110 V at 70 r/min. The maximum alternator power was 9.2 kW, measured at 150 r/min, for all loads tested.

Two three-phase motors rated at 5.6 kW and 7.6 kW were individually operated with an adjustable load developed by using a hydraulic pump. The hydraulic pump was in a closed-loop system with a heat exchanger which converted the motor power to heat. Motor speed and motor torque increased as the input frequency increased to the motor. The load was varied by a valve which was used to regulate the flow of hydraulic fluid through the system. All motor speeds and torques were measured by a torque sensor with rotary pickup, and data recorded with microprocessor.

The four pole induction motors were rated at 230 V and 1,750 r/min. The motors, with Class B insulation and NEMA Design Code B, were designed for continuous operation with a service factor of 1.15. The 5.6 and 7.6 kW motors had identical nameplate information except for the current, which was 21 and 26 A, respectively. The nameplate V/f ratio calculated from 230 V and 60 Hz was 3.8.

Baseline data for each test was established by operating a motor with power from the utility. In the laboratory test, the alternator was then driven at preselected rotational speeds from 70 to 150 r/min to supply power to a motor. During field testing, the alternator speed varied according to the windspeed. Data were averaged on 15 second intervals, and the method of bins was used to combine the data.

Results

The voltage from the alternator was lower than the motor's nameplate values of 230 V for all tests (Fig. 2). The balanced three-phase line voltage ranged from 85 to 99 V at 70 r/min

[3]Trade names and manufacturer's model numbers are given for informational purposes only. Wind units used in USDA research were purchased by USDA through competitive bids. No endorsement is given or implied by any manufacturer.

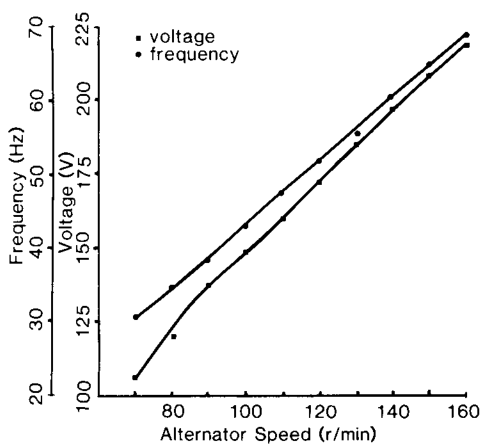

Fig. 1 Measured voltage and frequency for various alternator rotational speeds with an 8 ohm resistive load

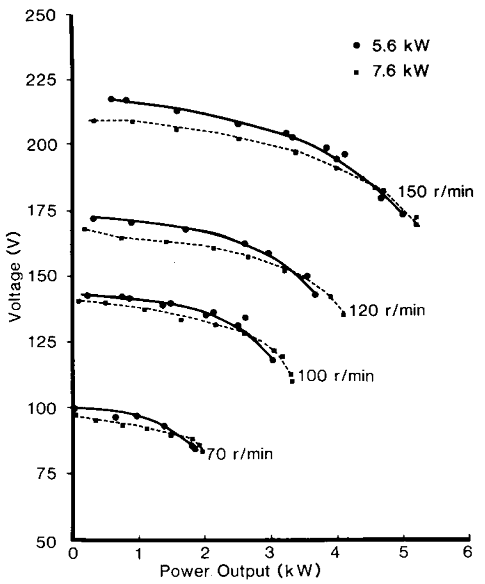

Fig.2 Line voltage versus motor power output of 5.6 and 7.6 kW motors with electrical power from alternator

Nomenclature

A	=	amperes
AC	=	alternating current
C_p	=	coefficient of performance
DC	=	direct current
Hz	=	frequency
kW	=	kilowatts
V	=	voltage
V/f	=	voltage to frequency ratio
WECS	=	Wind Energy Conversion System

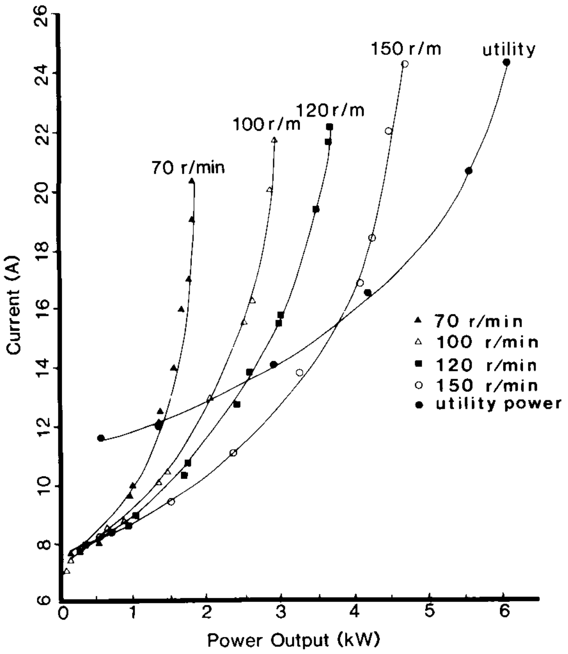

Fig. 3 Current versus motor power output of 5.6 kW motor with electrical power from utility and alternator

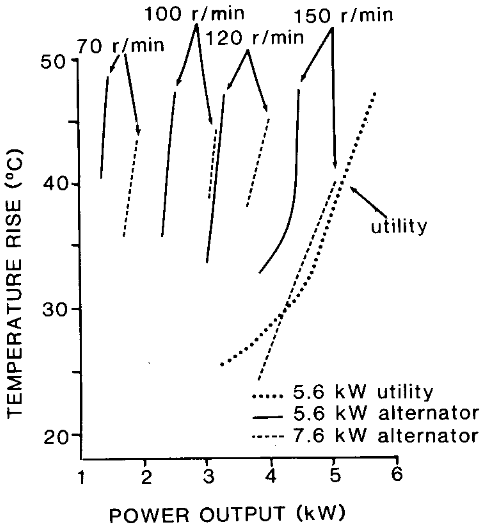

Fig. 4 Temperature rise above ambient versus motor power output for 5.6 and 7.6 kW motors with electrical power from the utility and alternator

and 170 to 218 V at 150 r/min. The V/f was 3.3 with no load on the motors and dropped to 2.6 when a motor approached its breakdown torque. The V/f was approximately the same for all the alternator speeds tested.

Figure 3 shows the effect of rotor speed on current and motor power output for the 5.6 kW motor. For a given power output, the alternator driven motor drew a larger current than the utility powered motor. Current requirements were less for the 7.6 kW motor than the 5.6 kW motor at power outputs above 3 kW.

Motor temperatures were measured by the insertion of thermocouples adjacent to the windings. Figure 4 shows the temperature rise above ambient of the motors at various motor power outputs. The 5.6 kW motor had a temperature rise of 44°C when producing 5.6 kW with utility power. Higher temperatures were recorded for power outputs below 5.6 kW when power was supplied by the alternator. When the

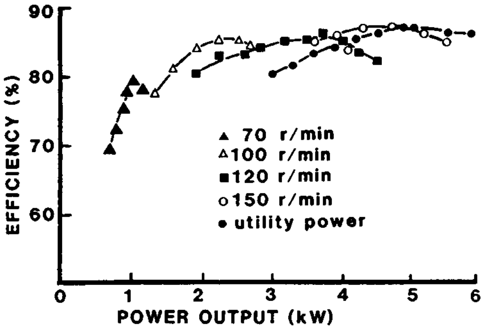

Fig. 5 Motor efficiency versus motor power output for a 5.6 kW motor when operated with electrical power from utility and alternator

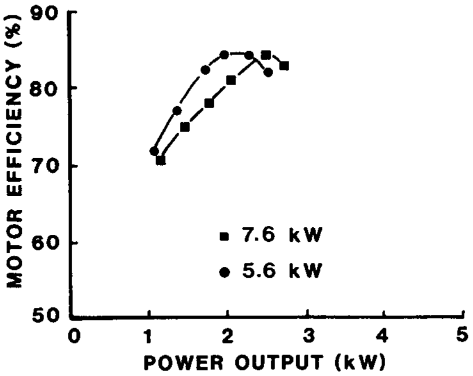

Fig. 6 Motor efficiency versus motor power output for 5.6 and 7.6 kW motors with alternator speed at 100 r/min

temperature rise was 40°C, a further increase in motor power output would result in a significantly increased temperature rise with alternator supplied power. The 7.6 kW motor had a cooler operating temperature than the 5.6 kW motor for a similar power output.

The motors with alternator supplied power attained peak efficiency below their ratings. Figure 5 shows the 5.6 kW motor efficiency versus motor power output for the utility and various alternator speeds. As power output approached 5.6 kW, the efficiency of the motor with the alternator dropped, while the efficiency of the motor powered by the utility remained constant. Efficiencies for heat 5.6 and 7.6 kW motors are compared at an alternator speed of 100 r/min in Fig. 6. Peak efficiency is approximately the same for the two motor sizes. However, they occur at different power outputs.

Figure 7 compares motor speed with respect to torque. The synchronous speed of a motor is a function of frequency, with the various alternator speeds being depicted by the distinct curves. The breakdown torque of the 5.6 kW motor ranged from 22 to 26 N-m for alternator speeds from 70 to 150 r/min, respectively. The slip of the motor did not significantly change with the substitution of the 7.6 kW motor, but the maximum torque did increase to 28 N-m at 120 r/min.

The Windworker 10 was operated for several months in the field with the hydraulic pump connected to the 7.6 kW motor. As the windspeed changed, the rotational speed of the alternator varied between 70 and 150 r/min, with a change in the voltage and frequency output. An increase in the frequency would cause a corresponding increase in the rotational speed of the motor and an increase in the motor torque (Fig. 8). The torque during the test varied from 12 to 25 N-m, while the power output of the motor changed from 0.8 to 5.0 kW. The motor efficiency for the test varied from 75 to 86 percent (Fig. 9). A temperature rise of 40°C above ambient for the motor was not exceeded while the system was operated in the field.

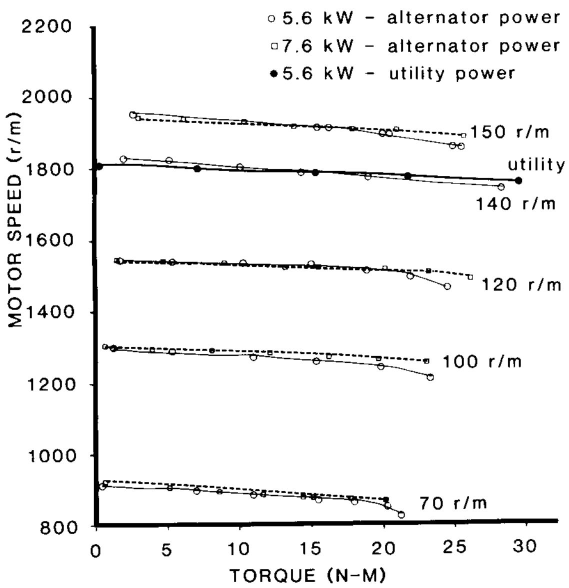

Fig. 7 Motor rotational speed in comparison to motor power output of 5.6 and 7.6 kW motors with electrical power from the utility and alternator

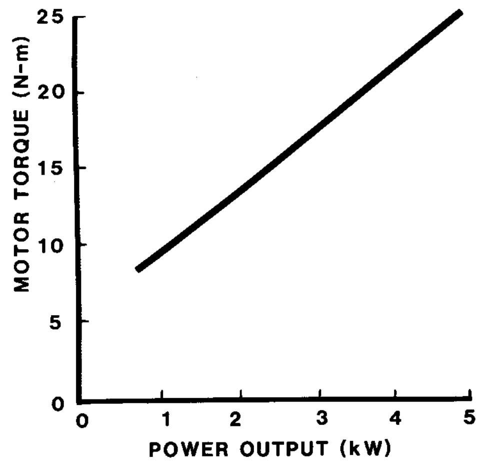

Fig. 8 Motor torque versus motor power output measured during field test of the 7.6 kW motor

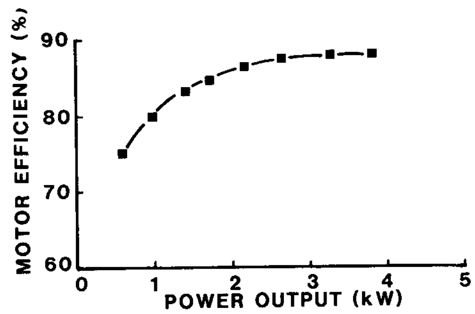

Fig. 9 Motor efficiency versus motor power output measured during field test of the 7.6 kW motor

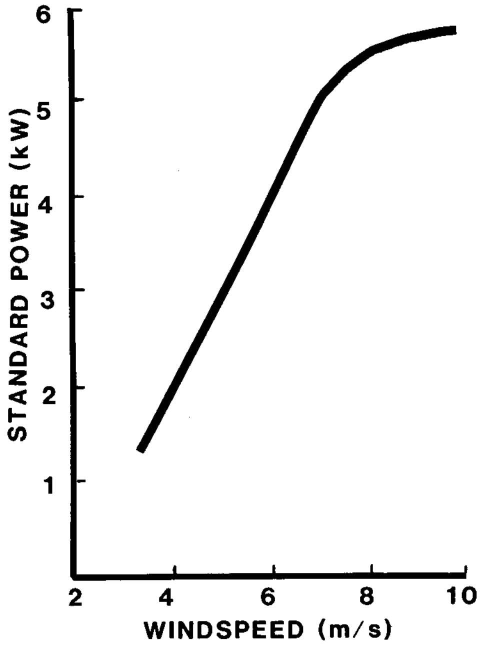

Fig. 10 Power curve (electrical) of the Windworker 10 measured during the field test using a 7.6 kW motor load

A power curve for the Windworker 10 was determined while loaded by the 7.6 kW motor and hydraulic pump (Fig. 10). The electrical power output of the alternator was ajdusted to a standard air density of 1.226 kg/m^3. The maximum power was limited by the breakdown torque of the motor [8]. Cut-in windspeed was 3.5 m/s, with the alternator reaching its peak output at 9.0 m/s.

Summary and Conclusions

A WECS using autonomous wind-generated electricity was satisfactorily operated in the laboratory and field. The permanent magnet alternator system, with output frequency from 30 to 65 Hz, provided power for resistive loads and induction motors. The induction motors, without significant increase in slip, operated at speeds from 800 to 1940 r/min. The voltage from the alternator ranged from 80 to 213 V, which was below the nameplate rating of 230 V. The lower voltage resulted in a larger current flow for similar power outputs when compared to operation with utility power. The V/f ratio varied from 2.6 to 3.3, which was below the nameplate of 3.8. Motor efficiency approached 86 percent with alternator power when the motors were partially loaded. At full motor rating, the variable frequency and voltage input was not capable of maintaining a high efficiency. The operating temperature of the 5.6 kW motor was higher than normal; however, a temperature rise of 40°C was not observed in the field test for the 7.6 kW motor. The total system was operated in windspeeds above 3.5 m/s, and the motor ouptut ranged from 0.8 to 5.0 kW.

It is desired that a variable-voltage, variable-frequency system operate at a constant V/f, near that specified by the nameplate of the motor. The system might be improved by using a self-excited alternator where the voltage is adjusted by the control system, which should be capable of operating near the optimum V/f. This would increase the breakdown torque of the motor and may increase overall system efficiency and performance.

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